CURRENT AND VOLTAGE-METERING MAGNETIC AMPLIFIERS

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Abstract.—Although the development and application of magnetic amplifiers for the measurement of direct currents and potentials is not new, recent improvements in core materials primarily of the so-called square hysteresis loop type have greatly increased the linearity and consequently the usefulness of these devices.

Inasmuch as the theory of operation has been reported previously, the emphasis has been placed on the design and performance characteristics of these devices. It is shown that such designs can be made insensitive to large changes in load resistance and a-c voltage and frequency. The use of a third winding for calibrating purposes is discussed as well as the application of metering magnetic amplifiers in monitoring the direct current and voltage in high voltage supplies for the Transatlantic Submarine Cable.

I. INTRODUCTION

Magnetic amplifiers for metering current and voltage have been developed with the desirable characteristics of extreme linearity and relatively wide operating ranges of power voltage and frequency and load impedance. These devices which are basically saturable reactors are not broadly new[1] and their analysis has been covered by many authors[2]. The application of recently available magnetic materials and careful attention to design parameters have made possible this improvement in performance of metering devices.

This paper describes briefly the operation of these devices and presents performance data that have been taken on units recently developed for use in metering the direct current and voltage powering the Transatlantic Cable. It is hoped that this information may assist circuit and equipment engineers in making more effective use of these devices.

II. MAGNETIC AMPLIFIER OPERATION

Basic Operation

The metering magnetic amplifier has been discussed in some detail by Storm and others[3]. The circuit consists essentially of two identical two-winding transformers connected with one set of windings in series and the remaining set in series opposition as shown in Fig. 1. In this arrangement, the fundamental and odd harmonics of the power frequency normally cancel in the d-c input or control circuit; but the even harmonics generated by the action of the cores produce a current which is limited only by the impedance of the control circuit. Thus two limiting modes of operation can be considered, the first in which the even harmonic currents flow freely and the second in which the even harmonic currents are completely suppressed. The impedance in the d-c circuit is relatively high in the case of current- and voltage-metering magnetic amplifiers. Therefore, only the latter mode of operation, usually called the constrained case, will be considered herein.

If we assume ideal cores having the B-H characteristics shown in Fig. 2(A) and a winding impedance in the saturated state which is negligible in comparison

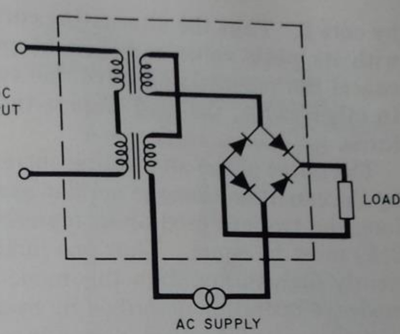


Fig. 1—Basic metering magnetic amplifier circuit.

to the load impedance, the magnetic amplifier operates as follows. A direct current in the input or control circuit establishes a working point P in the saturated regions of each core as shown. With an application of an a-c voltage the alternating current rises instantaneously until it just cancels the d-c magnetization in one of the cores. At this moment the working point on the characteristic of core 1 has reached the knee of the hysteresis loop and moves into the unsaturated region in the direction of point A. The current I assumes its peak value and any further increase in load current is limited because coil 1 now absorbs that portion of the voltage in excess of the voltage required to sustain the load (IR).

The current I remains at the peak value until core 1 under the cyclic excursion of the a-c voltage returns once more to the knee of the hysteresis loop, as shown by the arrows, and moves in the direction of P. During this period, which encompasses one-half cycle, core 2 remains in the saturated state and traverses the path indicated by the arrows shown in Fig. 2(A). One-half cycle after the start of this process cores 1 and 2 interchange roles so that core 2 is driven from the saturated into the unsaturated region and the reversal of current is limited

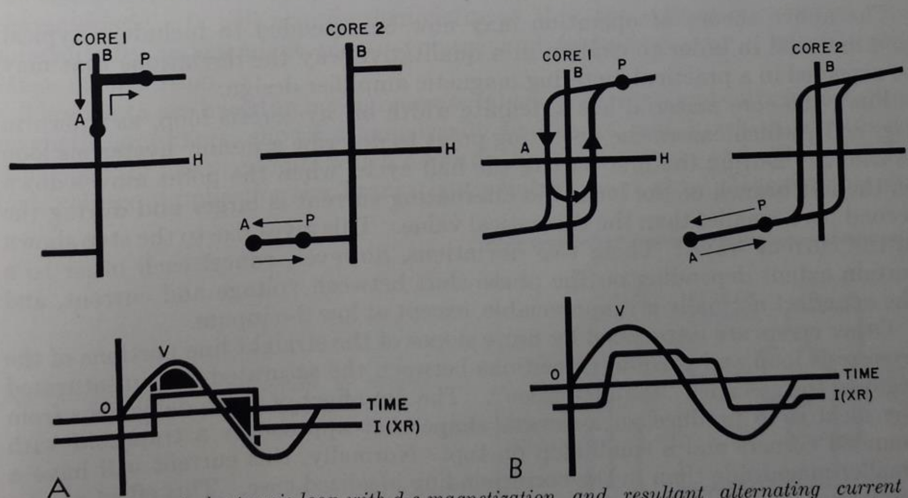


Fig. 2—Dynamic hysteresis loop with d-c magnetization and resultant alternating current wave shape I. (a) Ideal core material gives rise to a rectangular current wave. (b) Typical operation exaggerated to show effect on current wave.

by core 2. Thus the alternating current assumes a rectangular shape, as shown, with its peak value sufficient to provide the magnetizing force necessary to cancel the magnetizing force due to the direct current in the control winding. In other words, the load ampere-turns are exactly equal to the control ampere-turns.

The phase of the alternating current with respect to the voltage is determined by the condition that the net flux swing of one core over one cycle is zero. Therefore, the two enclosed areas representing the volt-time integrals shown in Fig. 2(A) must be equal. Thus one limitation on the a-c voltage is that it be sufficiently high to maintain this mode of operation. This is the first of the four modes of operation described by Storm[2] and covers the range in which metering magnetic amplifiers are normally operated. The a-c voltage is sufficient to sustain the load voltage IR but not so great as to cause a flux swing in either core in excess of twice the saturation flux under any operating conditions. The lower boundary of this mode of operation is reached when the load voltage is increased or the a-c voltage is decreased so that the load voltage wave is displaced to the left or away from the crest value of the voltage and the square wave just touches the sine wave. The average value of the voltage across the load resistance, R, is then 0.76 times the rms value of the sinusoidal alternating voltage. The minimum alternating voltage required to obtain a desired voltage across the load resistance, R, may thus be determined. Between these two extremes of a-c voltage the load current will remain proportional to the direct current in the control winding.

Thus if direct current is applied to the control windings, and alternating voltage of the proper magnitude to the power windings, an alternating current will flow in the power windings the magnitude of which is proportional to the direct current. The rectification of this alternating current will give a direct current which is proportional to the current in the control winding.

Effect of Core Material

The above theory of operation may now be extended to include a typical core material in order to explain in a qualitative way the deviations that may be expected in a practical metering magnetic amplifier design.

First, the core material has a definite width of hysteresis loop, as shown in Fig. 2(B), which causes the operating point to describe a minor hysteresis loop as shown. During the first part of the half cycle, when the point moves down on the left branch of the loop, the alternating current is larger and during the second part, smaller than the theoretical value. This gives rise to the step shown in the current wave. These two deviations, however, cancel each other to a certain extent depending on the phase shift between voltage and current, and the net effect normally is inappreciable, except at low d-c inputs.

Other errors are introduced by finite slopes of the straight line portions of the hysteresis loop and gradual transitions between the saturated and unsaturated regions, the so-called "rounded knee". The net effect of these deviations from the ideal is to produce an a-c wave shape that approaches a trapezoid with rounded corners and a small step on top. Normally, this current will have a smaller magnitude than in the corresponding idealized case. This effect can be minimized or eliminated by careful selection of the magnetic amplifier circuit constants in relation to the a-c voltage and frequency ranges.

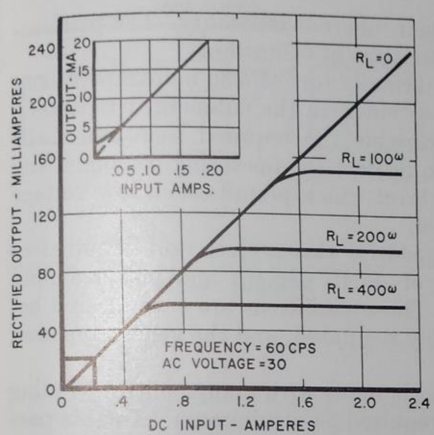


Fig. 3—Transfer characteristic indicating output is essentially independent of value of load resistance over a wide range.

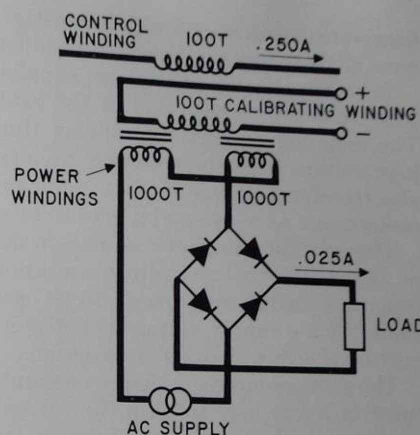


Fig. 4—Schematic arrangement of magnetic amplifier for metering current in high voltage circuit.

III. PERFORMANCE

Current and Voltage Metering

Metering magnetic amplifiers are sometimes called "d-c transformers" because the output current when rectified is related directly to the d-c input by the turns ratio of the two windings as shown in Fig. 3. This relationship is independent of the load resistance. However, as will be noted, the range of linearity is decreased as the load resistance is increased.

This range may be extended under some conditions by increasing the a-c voltage. The exciting current required by the cores precludes the linearity of the characteristic at very low input currents as shown in the lower end of the characteristic. It will also be demonstrated that the output current may be substantially independent of a-c voltage and frequency over a considerable range of operation.

These data are based on measurements taken on current- and voltage-metering magnetic amplifiers, shown schematically in Figs. 4 and 5, which have been developed for use in circuits which monitor the direct current and voltage of the high voltage supplies for the Transatlantic Submarine Cable. Magnetic ampli-

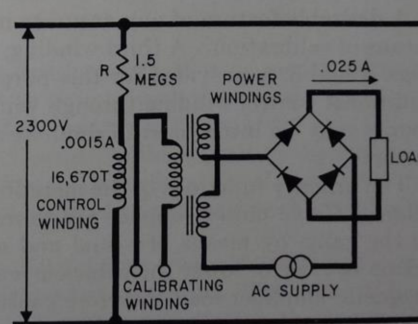


Fig. 5—Schematic arrangement of magnetic amplifier for metering high potential.

fiers were chosen specifically because of their inherent reliability. The performance of these units is discussed to illustrate typical operation.

In this application, the power supplies normally furnish 230 milliamperes and 2300 volts d-c to each end of the cable to energize the submerged repeaters. The metering magnetic amplifiers thus provide the required isolation of the high voltage from the metering circuits to protect the operating personnel and also transform the metered currents to a level which permits such low voltage components as relays and diodes to be used.

The metering magnetic amplifiers designed for this project were required to be insensitive to line voltage variations of + 15 percent and power supply frequency variations from 47 to 63 cps. These variations are encountered because the a-c supply voltage is not precisely regulated, and the generators used may be of either 50 or 60 cycle design.

The voltage-metering magnetic amplifier is made with many control winding turns of a fine wire to keep the current required to a minimum. In this particular unit, the turns ratio of the control winding to the power winding is 16.67 to 1. Consequently, a direct current of 1.5 milliamperes in the control winding causes a rectified output current of 25 milliamperes to flow in the load circuit.

It was essential in this application to keep the a-c supply voltage and the turns ratio of the windings to a minimum commensurate with the requirements of linearity of the magnetic amplifier to minimize the second harmonic ripple induced in the cable circuit. Assuming a nominal a-c voltage of 30 volts, there would be induced a maximum of three volts rms across the control winding of the current magnetic amplifier and as much as 500 volts rms across the control winding of the voltage magnetic amplifier. Although these ripple voltages seem high, the impedances of the circuits provide considerable suppression of the ripple current.

It will be noted that there is associated with each voltage-metering magnetic amplifier a high valued series resistor. Obviously, this resistor must be of constant value and of low temperature coefficient since the magnetic amplifier is sensitive to current through its control winding rather than voltage. Inasmuch as the control winding resistance is small, about 3800 ohms, compared to the series resistor of 1,500,000 ohms, no compensation for changes in the winding resistance caused by ambient temperature variations is required.

Calibrating Winding

A desirable feature of any accurate measuring device is a simple and reliable means of calibration. A third winding, called the calibrating winding, shown in Figs. 4 and 5, is provided for this purpose. This winding is in effect a bias or additional control winding through which a test current from a low voltage d-c source may be introduced to simulate a change in the current or voltage being metered.

The primary functions of the metering magnetic amplifiers used in the Transatlantic Cable power supplies are to monitor the current and voltage supplied to the cable by means of visual and aural alarms and to institute corrective action to raise or lower the cable current or voltage when the need arises. The magnetic amplifier load therefore consists essentially of a relay through which the alarm and corrective circuits are operated.

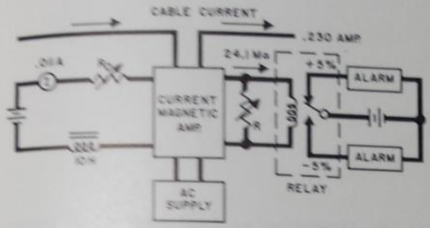


Fig. 6—Method of calibrating alarm circuit operated by magnetic amplifier provided with additional winding.

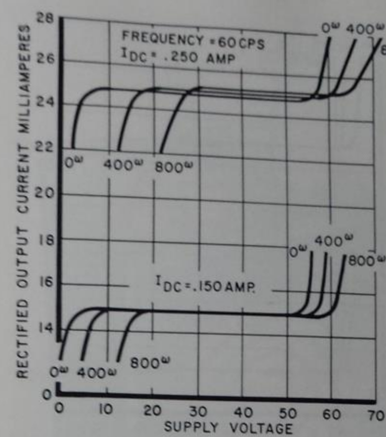


Fig. 7—Wide variations in applied a-c voltage have no appreciable effect in the operating range.

Figure 6 illustrates how the alarm circuits may be adjusted and tested. In this particular application the cable current is normally maintained at about 230 milliamperes, and the current-metering magnetic amplifier is required to actuate an alarm if the current increases or decreases five percent. Therefore the rectified output of the magnetic amplifier is supplied to a sensitive relay which operates to close a high contact at 21 milliamperes and a low contact at 19 milliamperes with a dead or nonoperate zone in between. When the cable current is at its nominal value, the 5,000 ohm rheostat R, shown on the diagram, is adjusted so that the moving reed of the relay is centered. A current equivalent to a five percent change in the ampere turns flowing through the control winding is then introduced into the calibrating circuit. Since the number of turns on the calibrating and control windings are the same, in this case it is sufficient to introduce a current equivalent to five percent of the cable current into the calibrating winding or, in this case, 11.5 milliamperes. If the direction of current flow in the calibrating winding produces a mmf which aids the d-c mmf by the control current, the output of the magnetic amplifier will be increased five percent and the high contact of the relay should close and operate an alarm circuit. Conversely, if this current produces mmf opposing that of the established control winding mmf, then the output will decrease five percent and the relay will close a low contact and operate another alarm circuit.

The voltage-metering magnetic amplifiers are adjusted in a similar manner.

A-C Supply Variations

If these alarm circuits are to perform satisfactorily, it is necessary that the magnetic amplifier output be insensitive to normal variations in the frequency and voltage of the a-c supply throughout the operating range of the control circuit. Figure 7 illustrates how extremely insensitive the output of the magnetic amplifier is to a-c supply voltage variations. The separation of the curves for the 250 ma signal has been somewhat exaggerated in this figure for clearness of representation.

In the Transatlantic Cable application 250 milliamperes is the expected maximum current and 200 milliamperes is the expected minimum. The nominal load resistance is approximately 400 ohms. The characteristic for the maximum

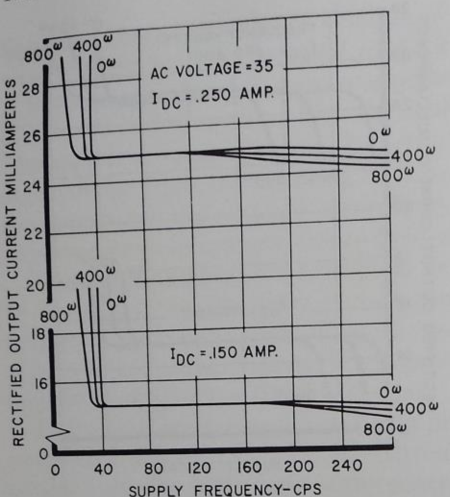


Fig. 8—Operation is independent of power frequency variations.

current condition indicates that the line voltage may vary from 19 to 57 volts or a range of 3 to 1 in voltage without affecting the output current of the magnetic amplifier. At lower values of load resistance and cable current the a-c supply voltage may vary over a wider range without impairing the circuit performance.

The lower ends of the characteristics droop because the a-c voltage is insufficient to sustain the required load voltage. Conversely, the upper ends of the characteristics rise because the a-c voltage is sufficient to swing the flux more than twice the saturation value, thus driving the cores into saturation and causing an increase in the load current.

The metering magnetic amplifier is also insensitive to frequency variations as may be seen in Fig. 8. It should be noted that the magnetic amplifier suffers no loss of accuracy for frequencies between 40 and 120 cps. Above the latter frequency, which is well in excess of the frequency range required for this application, the characteristics of the hysteresis loop are altered, tending to make the current wave shape more rounded and thus reducing its value. As the supply frequency is lowered without altering the a-c voltage level, the flux swing in the cores encompasses a greater portion of the hysteresis loop until finally the flux in the cores tends to exceed the saturation flux and thus the load current increases abruptly as shown. If the a-c voltage is reduced, the accuracy of the magnetic amplifier may be maintained to even lower power frequencies.

IV. DESIGN

The current-metering magnetic amplifier developed for the Transatlantic Cable application is shown in Fig. 9, and the voltage-metering magnetic amplifier is similar to it in appearance. The cable current passes through the control winding by means of the tall, coaxial terminal shown. A second pair of terminals designated 3 and 4 is provided for the calibrating winding, and a third pair designated 1 and 2 for applying the alternating current to the power windings.

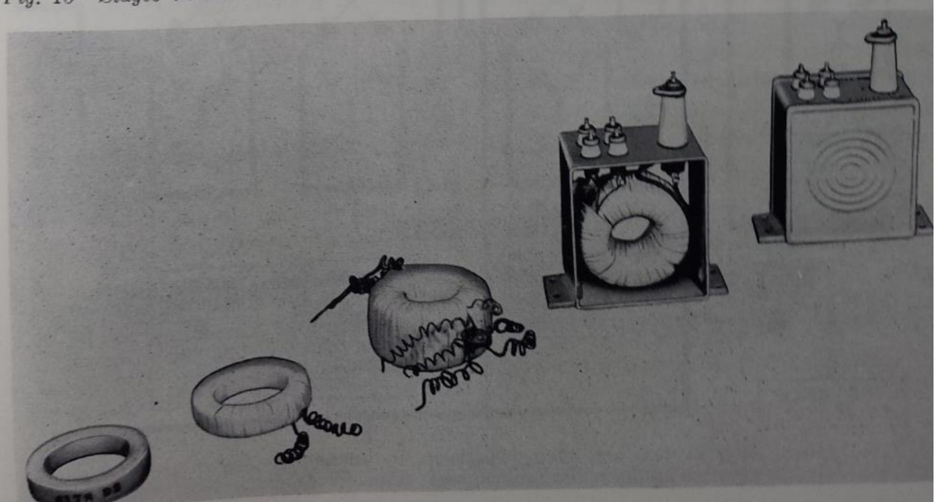
The entire unit is oil impregnated and hermetically sealed. The use of oil as the dielectric assures adequate dielectric strength between all windings and

Fig. 9—Current metering magnetic amplifier designed for use in Transatlantic Submarine Cable Power Supply. The d-c winding may be operated continuously at 7.5 kilovolts above ground.

the case of the unit. These units are capable of corona-free operation with rms voltages up to 7,500 between control windings and all other windings and case, which is well beyond any trouble or transient condition likely to be encountered in service. Actually, the high voltage bushing, rather than the internal structure of the unit, constitutes the limitation on this voltage.

Internal details of the magnetic amplifier are shown in Fig. 10. The magnetic core shown at the lower left is spirally wound of a 50-50 nickel-iron alloy tape

Fig. 10—Stages in the assembly of the current metering magnetic amplifier shown in Fig. 9



of two mils thickness, which as a result of special processing has a rectangular hysteresis loop. This core material is obtainable under the trade names Deltamax, Orthonol, and Hipernik V. These cores normally are furnished in sealed cases containing a small amount of oil or grease to protect the core from mechanical shock which might adversely affect the core characteristics.

To the right of the core is shown a core with its 1000-turn power winding applied and a layer of cotton tape wrapped over the winding. Two power winding and core assemblies are then placed on opposite sides of a flat mounting detail and the control and calibrating windings wound around this assembly. The electrical insulation necessary for high voltage operation is provided by including layers of cotton tape between the windings. This assembly is shown in the center of Fig. 10.

Next toward the right is shown a complete winding and core assembly fastened into the metal case by two mounting screws. At the extreme right may be seen the completely assembled magnetic amplifier. The concentric rings which are visible in this view are embossed in thin steel covers which flex as the oil contained in the case expands and contracts with changes in temperature.

V. CIRCUIT APPLICATION

Figure 11 shows how the current-and voltage-metering magnetic amplifiers are employed in the Transatlantic Cable power supplies. This circuit has been somewhat simplified and is shown primarily to illustrate the functions performed by the magnetic amplifiers.

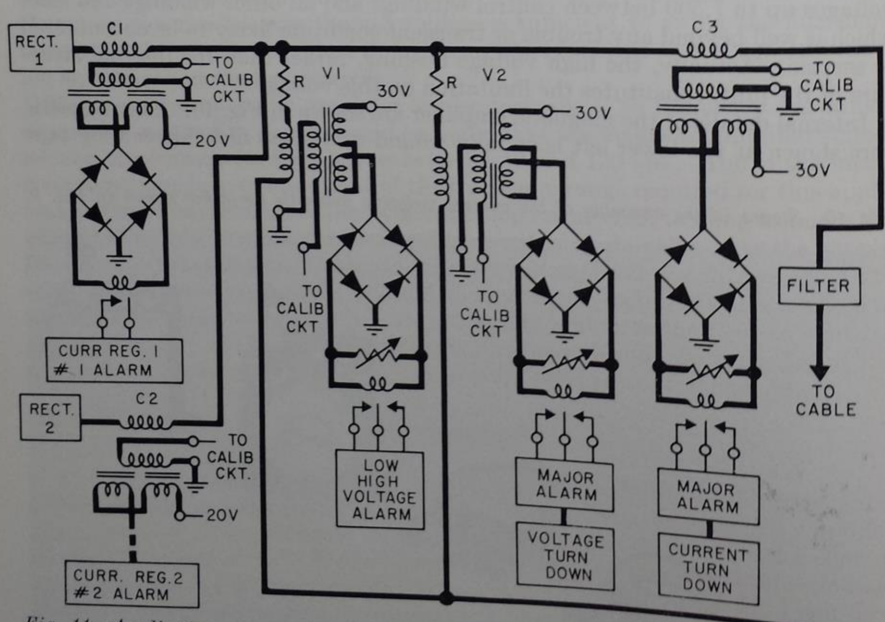


Fig. 11—Application of current and voltage-metering magnetic amplifiers in the high voltage power supply of the Transatlantic Submarine Cable.

The magnetic amplifiers identified as $C1$ and $C2$ are associated with two direct current supplies, each of which provides one-half of the required cable current. The magnetic amplifiers are intended to actuate alarms if their associated current supplies fail to provide their shares of the cable current.

The magnetic amplifier identified as $C3$ monitors the total cable current and its primary function is to safeguard the cable from an abnormally high current which might shorten the life of the underwater vacuum tube repeaters. In addition, through a servo system, the magnetic amplifier may exert the necessary corrective action to reduce the cable current to a safe value.

The voltage-metering magnetic amplifier designated as $V1$ actuates a high alarm when the cable voltage rises by five percent from a preset value and another alarm when the voltage decreases from this present value by an equal amount. The operating voltage of the cable is expected to be between 1900 and 2400 volts d-c, depending upon the current desired and the earth potential variations.

The voltage-metering magnetic amplifier $V2$ will actuate an alarm if the circuit voltage exceeds a certain limit and also can institute the necessary corrective action to restore the cable voltage to a safe value through a servo system.

VI. CONCLUSION

What then are the desirable features of the metering magnetic amplifier? First, the device functions as an instrument transformer converting one direct current level to another with a high degree of accuracy. Secondly, the magnetic amplifier provides an isolated output which may be held at low potential to ground regardless of the potential of the circuit under measurement. In addition, the power required to operate these devices is consistent with other means of measurement and wide variations in temperature do not impair the accuracy.

Performance data have been reported which indicate that these units have extremely linear transfer characteristics over a wide range of d-c input currents. Specific designs have been discussed in which this linearity has been maintained within one percent over a 2:1 change in input current as the a-c voltage and frequency vary as much as 2:1 with a moderate output load. This accuracy is improved and the operating range is extended as the output load is decreased.

The construction of this device is simple and follows standard transformer practice. The use of an additional control winding, called in this paper the calibrating winding, has been demonstrated to be highly useful in applications of this device.

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